Project Title: Multi-Purpose robotic system for orchards

Report Type: Final Project Report

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Cooperators: Stemilt, Columbia Fruit Packers,

Project Duration: 1 Year

Total Project Request for Year 1 Funding: $ 175,000
Total Project Request for Year 2 Funding: $
Total Project Request for Year 3 Funding: $

Other related/associated funding sources: Awarded
Funding Duration: 2022
Amount: $100,000
Agency Name: Western Growers Service Corp
Notes:

WTFRC Collaborative Costs:

Item	2022	(Type year start date of year 2 here if relevant)	(Type year start date of year 3 here if relevant)
Salaries			
Benefits			
Wages			
Benefits			
RCA Room Rental			
Shipping			
Supplies			
Travel			
Plot Fees			
Miscellaneous			
Total	$0.00	$0.00	$0.00

Footnotes:

Budget 1
Primary PI:
Organization Name: FFRobotics
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Station Manager/Supervisor:
Station manager/supervisor email address:

Item	(Type year of project start date here)	(Type year start date of year 2 here if relevant)	(Type year start date of year 3 here if relevant)
Salaries	$38,936.00		
Benefits	$11,681.00		
Wages	$33,075.00		
Benefits	$3,308.00		
RCA Room Rental	$25,000.00		
Shipping	$16,000.00		
Supplies			
Travel	$22,000.00		
Plot Fees			
Miscellaneous	$25,000.00		
Total	$175,000.00	$0.00	$0.00

1. OBJECTIVES

The following are the project objectives.

1) Integrate and demonstrate multi-arm harvesting robot to cover entire tree height
2) Evaluate the performance of the harvesting robot while in motion
3) Improving robot throughput
4) Demonstrate integration of the harvesting robot with fruit conveying and bin filling system

Obj. #	**Research Activities**	**Time**			
		H1		H2	
1	Updated graphics				
	Updated Platform (Automated Ag integration)				
2	Improve picking Mechanism (Grippers and Software)				
3	Lab Testing - WSU Sunrise Research Orchard				
	Field Testing Commercial orchard				

2. SIGNIFICANT FINDINGS

The most important accomplishment of this project is that we were able to build a full-scale integrated system and evaluate it in Washington, which shows that robotic apple picking is a working system.
The trials in Washington also exposed us to new apple varieties, including Gala, Honeycrisp, CosmiCrisp and Kanzi, which added substantial data to our continuing efforts to improve the FFRobot.

- The fruit detection algorithm developed based on a deep learning technique worked properly. The technique and technology used also detect obstacles such as branches and trellis wires.
- There is a need for different harvesting movements based on the specific variety.
- The multi-arm system was working with minimum interferences between the different arms.
- The robotic system can now work in 10-14 foot rows. Work is to be done to improve the throughput of the entire system.
- The analysis of robot limitation and the description of the suggested setting of the fruit is underway.
- The flexible joint in the gripper improves the quality of harvesting, limits bruising

3. Harvesting Objectives 1 to 4:

3.1) Integrate and demonstrate multi-arm harvesting robot to cover entire tree height

Following the challenges we faced during the 2021 season, we will work on the integration during the winter and test the integration solution in Automated Ag facilities before the season (running the integrated solution ahead of August 2022 (minimum two-shift in a roll)
Automated Ag team lead this objective in collaboration with FFRobotics team.

Materials: The current Engine/Generator solution failure prevents working for more than a few hours. We need to upgrade the HW system to facilitate the required 24/7 working methods.

Procedure: Installing the new integrated solution of Motor/Generator and testing it in the Automated Ag shop for a few shifts in a roll to make sure it is working correctly.

Done- we did not face major issues with the Engine/Generator solution.

3.2) Evaluate the performance of the harvesting robot while in motion

Following the challenges we faced during the 2021 season, the current integrated solution was not tested. W*e will try and improve the integrated solution before the season and at Automated Ag facilities before the season.* FFRobotics team will lead this objective in collaboration with the Automated Ag team.

Materials:
Testing bins handling. Bin Loading / Unloading
The unload bin system we implement in the robot is working in two stages: the fork going down and only in the last stage the tilt appears

Procedure:
Loading and unloading bins before the season.
Make sure we can do it with the supervisor of the robot. Testing the unload bin system that is now working in two stages: the fork going down and only in the last stage the tilt appears

Done -the system is working correctly and bins are successfully unloaded. There is a need to automate the process to shorten the cycle time

3.3) Improving robot throughput
Improve the number of bins per hour (including the bin loading and replacement)

Materials:
Upgrade the system's computing power and improve the harvesting algorithms and bin handling.

Procedure:
There are 4 layers to improve *robot throughput of the system:*

1) Upgrade the PC and the GPU card,
2) Software improvements (software processing time that are not related to the HW)
3) Procedure improvements during harvesting - load bins/unload bins, movements between stages
4) Improving the end effector

We are now working on the 4 layers:

1) New HW
2) SW improvements in the main controller and low-level controller
3) Based on objective 3.2 to implement the best harvesting procedure

4) Improve the end effector, flexible grippers to avoid toque issues, and avoiding unnecessary movements of the arms

Done, but further work is needed to improve the robot throughput of the system.

1) ***New HW – installed new PC with a new GPU – Processing time is 8 times faster.***
2) ***Robot throughput of the system – We have made ongoing upgrades during the season and are still working to improve the SW. Work is being done to evaluate the improvement of changing the arm design.***
3) **implement the best harvesting procedure – done**
4) **Improve the end effector: flexible grippers – done (two cycles)**

3.4) Demonstrate integration of the harvesting robot with fruit conveying and bin filling system
Demonstrate a complete solution in a commercial orchard.

Materials:
The upgraded FFRobot in the Commercial orchard

Procedure:
Harvest starting at WSU Sunrise Research Orchard with the FFRobotics team – Target date Aug 1st 2022.
Testing the system's improvement to make sure no degradation following the changes, using the same harvesting method and capacity.
Increasing the capacity while ensuring the harvesting quality remains at the right level.
Following reaching the maximum capacity moving to the commercial orchard (Columbia Fruit) Target Date – no later than Aug 20th

Done:
We signed a commercial agreement with one of the Cooperators. Based on the customer request and the season's development, we arrived at the commercial orchard by Aug 15, and worked till the end of October. The quantities we picked were not as expected and we did not reach the commercial quantities.

Collaborators (to be secured by WFTRC, in-kind contribution):

- Advisory team (frequent input throughout the entire season): interested technology/apple horticulture committee members, growers in Ephrata area
- WTFRC and WSU postharvest ITT will independently evaluate fruit quality (bruising, stems etc.)

4. RESULTS & DISCUSSION

4.1 Obj.# 1 Integrate and demonstrate multi-arm harvesting robot to cover entire tree height

Following the challenges we faced during the 2021 season, we integrated a new coupling between the Generator and the Motor. We tested the solution at Automated Ag facilities before the season (running the integrated solution ahead of August 2022).

We did not face any major mechanical failure during the season, and we feel comfortable with the current integration,

4.2 Objective # 2,3 Evaluate the performance of the harvesting robot while in motion & Improving robot throughput

FFRobot designed as a full-scale robotic harvesting systems. The commercial-ready mechanical prototype was used in the field trials in Washington and Israel. The robotic picking mechanism was integrated with a dedicated platform from Automated Ag Systems and a dedicated convey system and Bin Filler from Maf Roda Industries, for evaluating the completed (end-to-end) harvesting process. Based on the feedback from the growers, we added a sorting/clipping station ("table") before the bin filler to enable the growers to implement the sorting /clipping manually before we automate this task in the future.

Images and videos have been collected and were processed for improved detection and localization of apples for fruit harvesting. Data were collected using an Intel RealSense 435 camera (Intel, USA) mounted on top of a robotic arm moving across its workspace.
In addition, the machine vision system, developed using a Mask RCNN (one of the latest deep learning techniques), was expanded to detect additional parts of tree canopies, including branches and leaves along with fruits, so that important orchard characteristics such as branch obstruction, occlusion and pseudo-pendulum effects can be detected, Fig. 2.
*The proposed method detected fruit parts with a mean average precision (mAP) value of 87% on a test dataset***Error! Reference source not found.***The binary mask obtained for each class from Mask-RCNN output was further analyzed to provide safe (avoiding apples that are occluded or not safe to pick for the given view) and reliable (providing right picking orientation by considering the fruits immediate surrounding) harvesting decision to the robot. With this proposed approach, the system was able to identify apples that were safe to harvest with 92% accuracy and was able to predict the fruits challenging to harvest with 91% accuracy compared to ground truth data. Though the current robotic system for picking may not utilize the variable approach direction, new capability of the vision system provides an improvement on the overall harvesting system.*

Fig. 2: The row data for harvesting based on MaskCRNN

In addition to branches and other fruit, trellis wires also presented significant obstacles to robotic picking and thinning. Trellis wires were only partially visible (in segments) in images due to their thin size, and occlusion due to branches and leaves. A trellis wire detection technique was developed utilizing binary line descriptors and Haar-like features were combined at the decision level. Segments of the trellis wires detected by the vision system were combined using Hough Transform so that wire location could be estimated in the occluded regions as well. Preliminary analysis showed the trellis wire detection F1-score of 83% (Fig. 3). This technique integrated with the current robotic harvesting system to avoid robot collision with trellis wires.

Fig. 3: Trellis wire and trunk detection to avoid end-effector and trellis wire collision. Even though only parts of the trellis wire are visible, the algorithm can reliably estimate the occluded part of the trellis wire assuming a linear geometry.

Fig. 4: Sample of before and after harvesting by the machine

The additional information gained with the improved algorithms, and the improved mechanism (additional degree of freedom – controlling the twist of the gripper), allowed us to catch the fruit based on the stem orientation and to twist each fruit based on its specific/particular orientation. Based on the tests and improvements over 3 years of this project, we reached a good result of picking fruits. Some challenges we faced in picking included picking with spurs or small brunches (7%-15%), and bruising rate of 6%.

"Blocked Apple" - an apple which we identified as one we cannot pick, are left behind in the sections we picked (Fig 4)

In vertical orchards & summer pruning (Non Fruiting Wall structure), we picked around 50% of the fruits, We need to discuss further the percentage we aim for the robotic harvesting. We demonstrated successful identification and harvesting of fruit doubles. We demonstrated night harvesting.

During the season we picked few varieties each one with its challenge to name a few:

1) *Gala- clusters of fruits*
2) *Honey Crisp- very sensitive, in some cases put fruit after fruit in the bin, while we are using the bn filler*
3) *Cosmic Crisp – we faced a lot of damage fruits (not related to the robot) the robot pick the entire fruits and we need to do the sorting on the sorting conveyors, size of the fruits*
4) *Fuji- fruits size - not homogeneous*
5) *Kanzi - picking with spurs or small brunches*

Based on our experience we build a different harvesting method based on the variety, pull, twist and pull, slow movement towards the fruits etc.

A general concern we can identify the number of fruits that fall during the picking process. We see it as a major issue, as if we pick 50-60% of the fruits we must make sure we are not causing loss by dropping fruits to the ground,

Fig. 5: Sample of Fruits on the ground Left- robot Right- hand picking

The solution is working hand in hand with the growers by pruning and thinning from one hand and deciding what fruits the robot pick to reduce the number of fruits we lose during the robotic harvesting.

Note that the implementation of the multi-purpose robot will expedite this process.

<u>Performance:</u>
The company invested a lot of efforts to improve the performance of the system, and a lot of work a head of us. The 4 main activities in this regard:

1) *New HW – installed new PC with a new GPU – 8 times faster*
2) *robot throughput of the system we have made on going upgrades during the season, still working to improve the SW.*
3) *implement the best harvesting procedure – done*
4) *Improve the end effector, flexible grippers – done (two cycles)*

We demonstrate a manual bin replacement process – but the process is currently manual, and we need to automate the process to reduce the cycle time.

It is an ongoing process to improve the system's throughput, from theoretical calculation to actual practice. It is related to the number of fruits per session, the accessible fruits, the success rate of picking and more.

Following the season, we are running in-depth study to determine the next steps to achieve our goal.

<u>4.3 Objective # 4</u> The upgraded FFRobot in the Commercial orchard
We signed a commercial agreement with one of the Cooperators. Based on the customer request and the season's development, we arrived at the commercial orchard Aug 15, and worked till the end of October. The quantities we picked were not as expected and we did not reach the commercial quantities.
Following the activities this year and the support of the WTFRC we have now a new 3 commitment letters for commercial harvesting next year.

Night harvesting

Day Harvesting

Harvesting during rain

Executive Summary

EXECUTIVE SUMMARY The Multi-Purpose Robot for apple trees. The *long-term* goal of this project is to develop an affordable, effective and *sustainable production* *system* for *apples* through adoption of integrated horticultural and engineering solutions. The Lessons from earlier efforts of Co-PI Kahani (FFRobotics), PD Karkee and other investigators, suggest that multipurpose platforms equipped with efficient and fast robotic mechanisms at a reasonable cost will be needed to streamline labor-intensive orchard operations (Pruning, Thinning and harvesting) . Furthermore, robotic systems must be developed in cohort with horticultural that optimizes the interaction between human, plant and robot. FFRobotics, is developing full-scale fruit-picking robots that consists of 12 arms supported by a low-cost machine vision system and has been tested in apple orchards in WA and Israel. While a single use in operation, harvesting is the first implementation, we believe that in order to have a sustainable solution we must develop a multi-purpose robot for the orchard.

While providing a harvesting solution is essential, for the first time the robot can show the apple distribution throughout a tree, row and block. Ultimately, data such as these will help decrease the growing costs for tree fruit by enabling precision farming to better target efforts and costs only where they provide benefit.

During the project, we developed and demonstrated an end-to-end solution for harvesting based on the current operations in the orchards. Bin pass through the system, we integrated our solution with WA local manufacturer Automated Ag Systems and use one the leaders in the packing house equipment to ensure the best quality fruits in the bin.

During the project, we improved the solution to support the WA common practice of 10-14 foot row, developed a few methods for picking the different varieties of apples, and demonstrated a working system is working day and night.

Throughout the field tests, the robot operated almost flawlessly, including operation in temperatures well above 100°F, or rain, with no failures caused by heat or continuous operation for the computers and cameras.

Although during 2022, the Robot throughput increased, the system still requires an optimization algorithm and further development to increase the throughput of another 4-6 times to achieve the economic justification.

The next phase of development will move the Multi-Purpose Robot toward production.